PURDUE UNIVERSITY THERMAL SCIENCES AND PROPULSION CENTER
SCHOOL OF MECHANICAL ENGINEERING—1882-1982
100 YEARS OF PROGRESS

MEMORANDUM

To: NASA Lewis Research Center
Thomas VanOverbeke, Contract Monitor

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RE: Progress Report for NASA Contract No. NAG-3-502 Covering the Period from July 1, 1984 to July 1, 1985

I. Experimental System Development

A. The LDV System

A two-color, two component LDV system operating in forward scatter has been developed in order to make simultaneous measurements of the axial and radial velocity components in an axisymmetric sudden expansion flow with and without combustion. The LDV system includes Bragg cell modulators in the four beam paths to allow a net frequency shift of 5MHz in both the green and blue beams. This permits an unambiguous measurement of negative velocities and also eliminates incomplete signal bias. The green beam probe volume has a waist diameter of 0.200 mm and is approximately 2mm long. The blue beam has a probe volume waist of 0.250 mm and is approximately 1 mm long. The scattered light from the probe volume is separated so that approximately 80% of each color passes to its respective photomultiplier tube by using a dichroic filter. Narrow bandpass filters are used to further filter unwanted signals before they are detected. A schematic diagram of the LDV system is shown in Figure 1.

The flow without combustion is seeded with oil particles (DOP) approximately 1 μm in diameter generated from a liquid atomizer followed by an evaporization-condensation unit. The flow with combustion will be seeded with 1 μm diameter aluminum oxide particles generated from a TSI model 3400 fluidized bed generator or from a home built cyclone type seeder, depending

upon which seeder gives the best results. No testing has been performed using aluminum oxide seed particles to date. From some preliminary testing using this LDV system (with seed particles generated from the liquid atomizer) maximum data validation rates were found to be approximately 15,000 and 5,000 samples per second for the green (axial) and blue (radial) components, respectively. It is not clear what the maximum simultaneous data validation rate is with the coincidence timing circuit operating because no readout of "coincident" data ready rate is available to monitor. From the preliminary data taken, it appears that maximum "coincident" data ready rates range between 1000 and 2000 per second. For this case, biased velocity data results as will be shown later.

In an effort to obtain accurate unbiased velocity data two approaches will be investigated. The first approach will involve minor LDV system modifications with the goal of improving the blue beam signal quality and therefore increasing the blue beam data validation rate to > 10,000 samples per second. If this can be accomplished the experimental technique for eliminating velocity bias by inhibiting the counter processors for a fixed time interval between samples, approximating equal time sampling, will be used [1,2,3,4,5]. If the signal quality of the blue beam cannot be improved, a velocity bias correction scheme will be used. The second approach involves validating two proposed velocity bias correction schemes. The two correction schemes of interest are the McLaughlin-Tiederman 2-D weighting correction [6,7] and the Barnett and Bentley time between data correction [8]. The two-component "corrected" data will then be compared to independent unbiased one-component data obtained using the interval sampling technique mentioned above in order to validate each correction scheme.

The data collection and processing system consists of two TSI model 1990 counter-type processors (one for each channel), a TSI model 1998 interface with coincidence timing electronics and a PDP 11/40 mini-computer with DMA capability. The digitized thermocouple signal will also be interfaced through the TSI 1998 interface so that coincident velocity-temperature data can be obtained (Figure 2). With this system it is possible to acquire velocity data from individual doppler burst signals at rates up to 50,000 samples per second (limited by seed density). The mini-computer and counter processors are also interfaced so that sampling can be controlled. This is accomplished with a hardware clock controlling the data-inhibit handshaking signals. The software developed for this experiment is capable of burst (measurement sampled and stored as soon as it is validated) or interval sampling. It can also access the extended memory in the PDP 11/40 allowing up to 96K words of data to be stored for each sample. The data reduction program calculates three types of statistics for each sample. These include the standard statistic, the McLaughlin-Tiederman 2-D weighted statistic and the time between data weighted statistic. Data points lying outside $\pm 3\ \sigma$

(selectable) are discarded and revised statistics are calculated. Histograms are constructed for both velocity components on the the terminal and can be routed to the line printer for hard copies. The data can also be stored on the hard disk.

B. The Test Rig

The flow system utilized in this experiment is illustrated in Figure 3. Air is provided by a radial fan blower followed by a flow conditioning section consisting of honeycomb flow straighteners. Fuel (gaseous propane) will be injected in the duct immediately following the blower through a multi-port manifold to give a homogeneous fuel-air mixture. The test section consists of a converging inlet nozzle with an exit diameter of 76.2 mm followed by a 152.4 mm diameter downstream section. This inlet was chosen to give a uniform inlet velocity profile. The static pressure drop across the nozzle is used to monitor the inlet flow condition. The test section was extruded from optical quality fused quartz and allows measurements throughout the flowfield for x/h values ranging from 0.3 to 14. The test section design is shown in figure 4.

C. Correction Lens

A correction lens to allow simultaneous axial and radial velocity measurements in a cylindrical tube has been designed and fabricated using the procedure described in ref. 9. The planar-concave cylindrical lens that corrects for the aberration induced by the quartz test section has a radius of curvature of 3.3528 m, a thickness at its center of 17.93 mm and a refractive index of 1.52. The correction lens insures that the orthogonal probe volumes (green and blue) intersect to within 100 μm along the length of the probe volume and to within 25 μm along the diameter of the probe volume. This forces the scattered light from the different colored probe volumes to come from approximately the same point. The correction lens system is comprised of two lenses, one on the transmitting side and one on the receiving side of the test section as shown in figure 5. This is due to the symmetry of the system. The lenses have to be moved away from the test section as the measurement point moves further off axis. A ray tracing program is used to determine the placement of the lenses and also gives the real probe volume intersection relative to the beam intersection if no test section or lens was present. Simultaneous axial-radial velocity measurements can be made out to a non-dimensional radius of approximately 85% with this system.

D. Thermocouple Probe

Temperature measurements in the reacting flow will be made with uncoated Pt-Pt 13% Rh thermocouples. The thermocouple probe will consist of a two hole ceramic insulator containing two 0.5 mm diameter thermocouple posts. A 25 μm diameter wire will be

butt welded to form the thermocouple junction suspended midway between the two larger posts. The posts will be separated by approximately 5 mm.

The frequency response of 25 μm diameter thermocouples is known to be about 20 Hz. In order to improve their frequency response, the thermocouples used in this investigation will be electrically compensated for thermal inertia [10]. This involves a differentiating type circuit that performs the operation $[1 + \tau (d/dt)]E$ on the thermocouple emf, E, where τ is the probe time constant. It essentially amplifies the high frequency components of the thermocouple signal in inverse proportion to their attenuation by thermal inertia. The compensation circuit was designed to give the thermocouple a flat response (independent of frequency) up to 5000 Hz. The compensated signals are then passed through a sample and hold unit followed by a 12 bit A/D converter linked to the data acquisition system. A schematic diagram of the compensation circuit fabricated in the electronics shop at Purdue is shown in figure 6. A Bode plot of an uncompensated, correctly compensated and overcompensated thermocouple signal is shown in figure 7. The compensation circuit is completed, but has not been used as no combusting flow experiments have been run to date. The temperature of the fluid will be measured with a thermocouple probe located next to the LDV probe volume as shown in figure 8.

II. Preliminary Experimental Data

A substantial amount of preliminary two dimensional data have been taken in an effort to validate the LDV system. The flow characteristics of the test rig, the correction lens performance and the data acquisition and reduction software. A free jet flow was used initially and later replaced by the more complicated axisymmetric sudden expansion flow. As mentioned earlier only non-reacting flow experiments have been run to date. The following data set was acquired using the 2-component LDV and data acquisition system described in the previous section.

The measurements were made in the axisymmetric sudden expansion flow (Figure 4) using the correction lens system. The inlet velocity was uniform with a value of 22 m/s corresponding to a Reynolds number of 5.5×10^4 based on step height. Seeding was provided by the liquid atomizer described earlier. The burst sampling technique was used to obtain all the data presented below. Because the data was biased due to the sampling method used, the McLaughlin-Tiederman 2-D correction was also applied. This preliminary data set consists of measurements across the radius of the test section at 4 non-dimensional axial locations (x/H = 0.3,2,4 and 6).

Figure 9 shows the mean axial velocities (corrected and uncorrected) at the four axial planes. Notice that the corrected data has lower values of mean velocity in the shear layer where

turbulence is high and has approximately the same value as uncorrected velocity in regions of low turbulence. This is the expected result and may indicate that the 2-D weighting "corrects" biased data to the true time averaged values. These preliminary measurements are presented only to demonstrate LDV system performance. They are known to suffer from inaccuracy as a direct result of (1) the slowly oscillating shear layer characteristic of this flow field and (2) the burst sampling technique. The first problem occurs because the data was gathered at a high rate. This means the entire sample (n = 6000) was collected in a very short time (typically < 2 sec) and the statistical parameters of the sampled data depend on when in the low frequency cycle the data is collected. The observed variation in the mean axial velocity due to this unsteadiness was up to 10%. This "inaccuracy" is much greater than the statistical error due to the finite number of samples taken. Typically, in a well defined experiment, mean velocities are repeatable to better than 1%. The second source of inaccuracy (the burst sampling technique) is a velocity bias problem. Although the 2-D bias correction was applied, it was found to over correct the results in regions of high turbulence. This was confirmed by comparing unbiased one-component (axial) data to the 2-D corrected data. More work has to be done to determine the errors involved due to velocity bias and over-correction.

Figure 10 shows the mean radial velocity component at the 4 axial planes. Not much can be said about the data except that the radial velocity is very low in this flow field and that more scatter is probably present due to that fact. The low signal quality of the blue beam could also be responsible for some of this scatter.

Figures 11 and 12 show the axial and radial normalized turbulence intensities, respectively. The 2-D weighted data show the correct trends [1,7] relative to the uncorrected (biased) data and reach the same maximum values as other investigators have found [1, 11]. Notice the shift in the locations of peak turbulence intensities depending on whether a standard or weighted statistic is used. These figures show the magnitude of error that can be caused by biased velocity measurements and illustrate that completely unbiased data are needed to improve existing time averaged turbulence models.

Figure 13 shows simultaneous Reynold's stress measurements made with the coincidence window set to 10 μs (the minimum value on the TSI 1998 interface). Again, significant differences exist between the corrected and uncorrected statistic in regions of high turbulence. Also, more scatter is associated with this statistic. Again, probably due to the low signal quality of the radial velocity component. However, the maximum values of normalized Reynold's stress agree well with other experimenter's values [11].

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11. Durrett, R.P., Stevenson, W.H. and Thompson, H.D., "Radial and Axial Turbulent Flow Measurements with an LDV in an Axisymmetric Sudden Expansion Air Flow," to be published, ASME Winter Annual Meeting, Nov. 17-22, 1985.

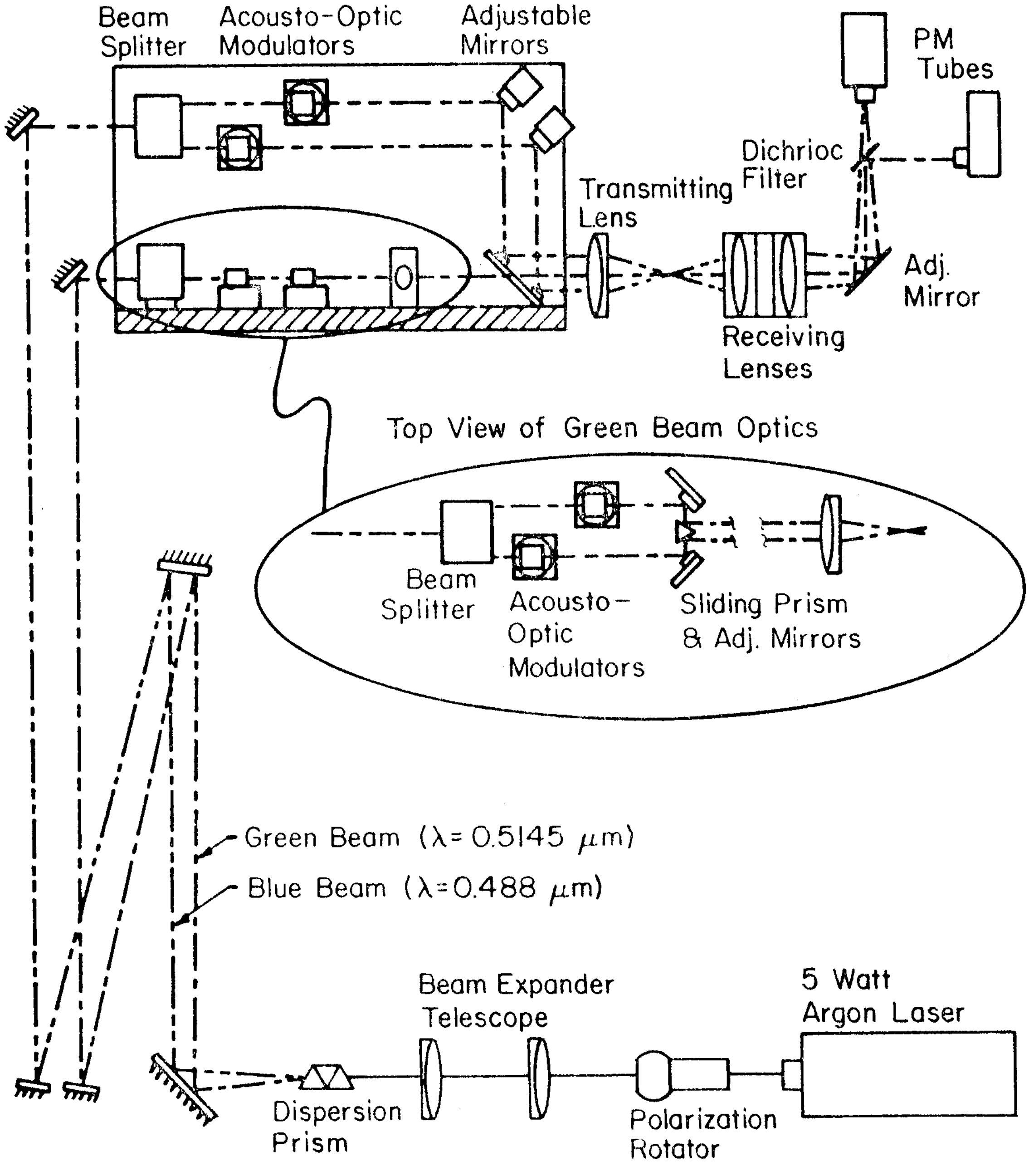

Figure 1. Two-component LDV system

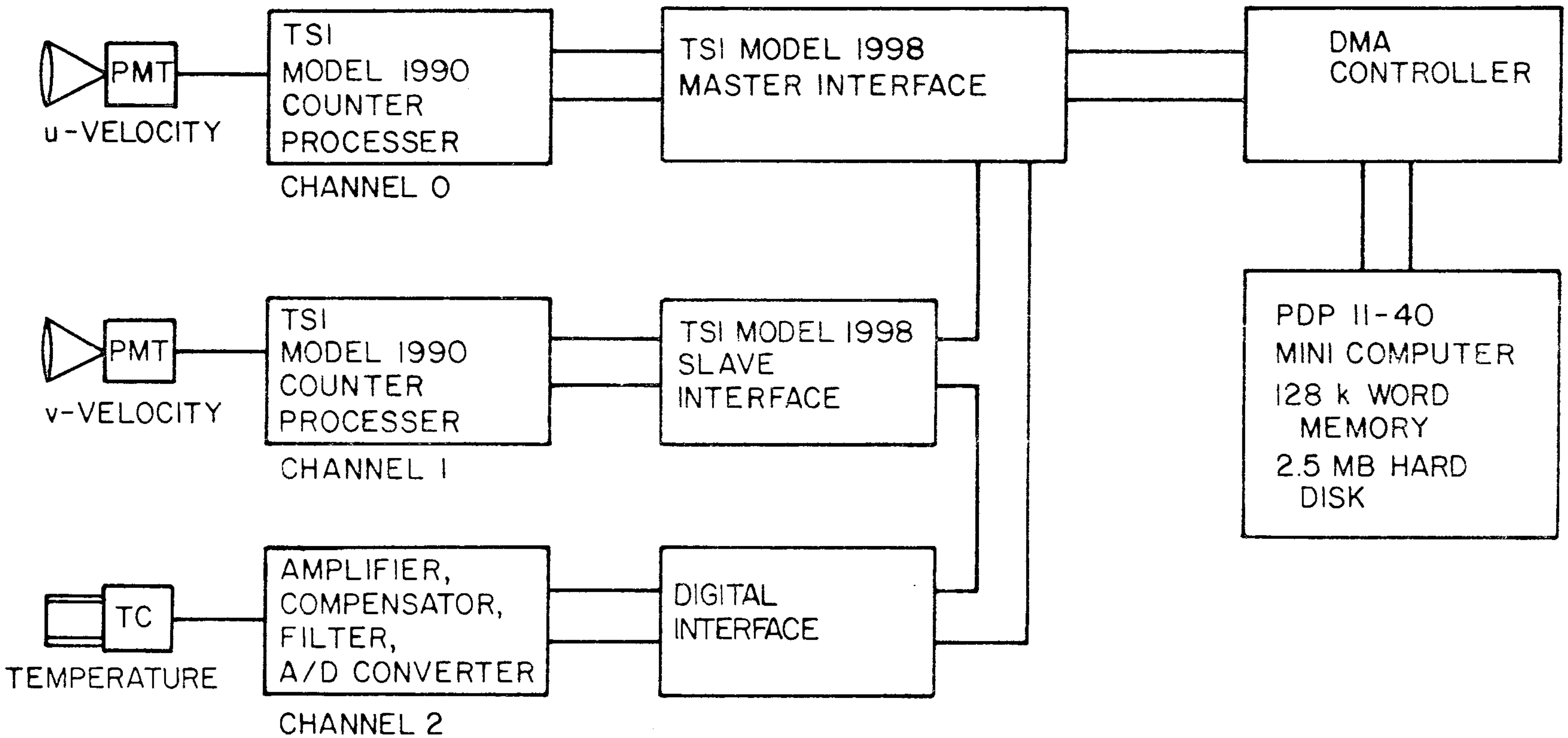

Figure 2. Data acquisition system

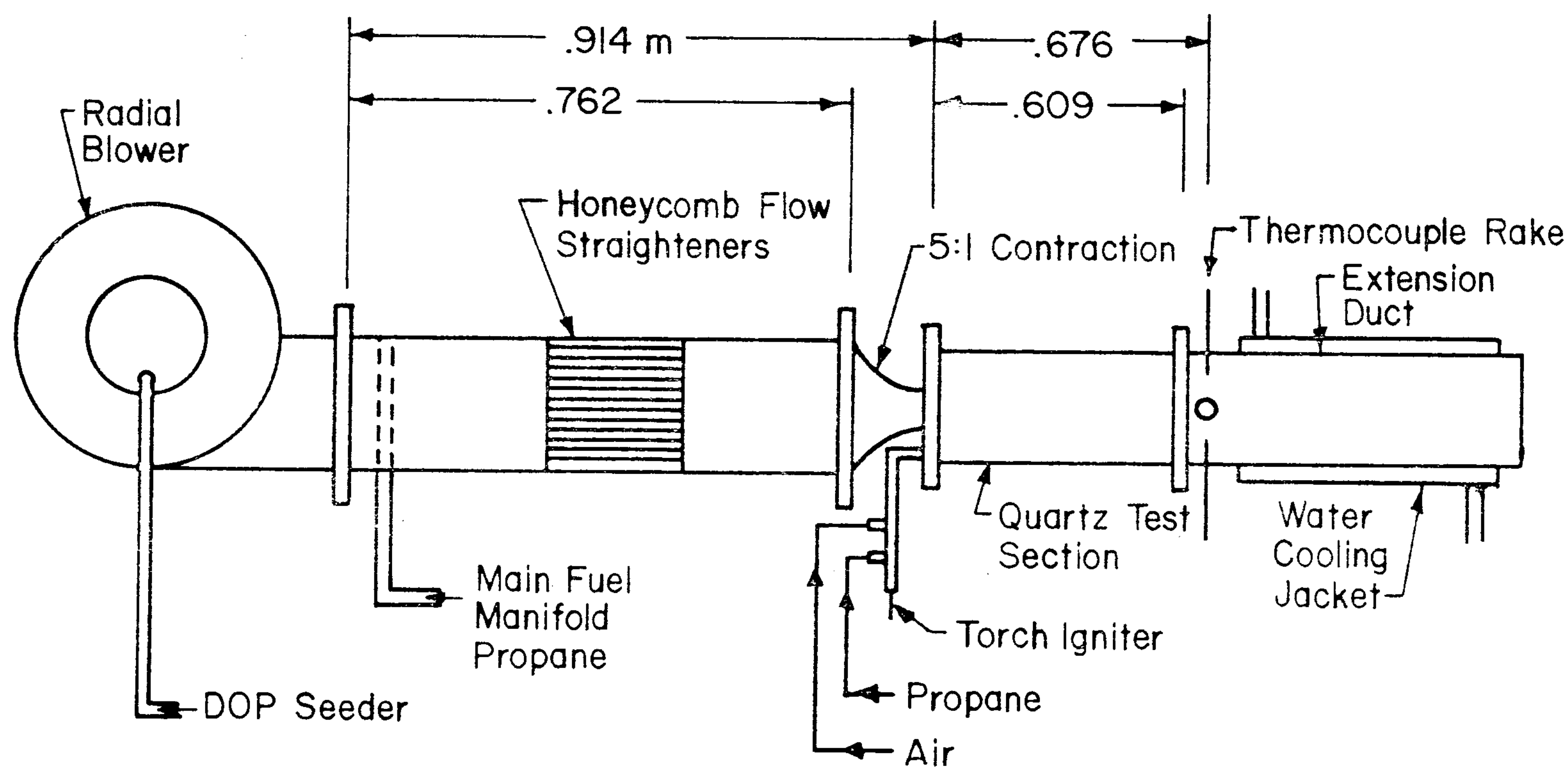

Figure 3. Flow system

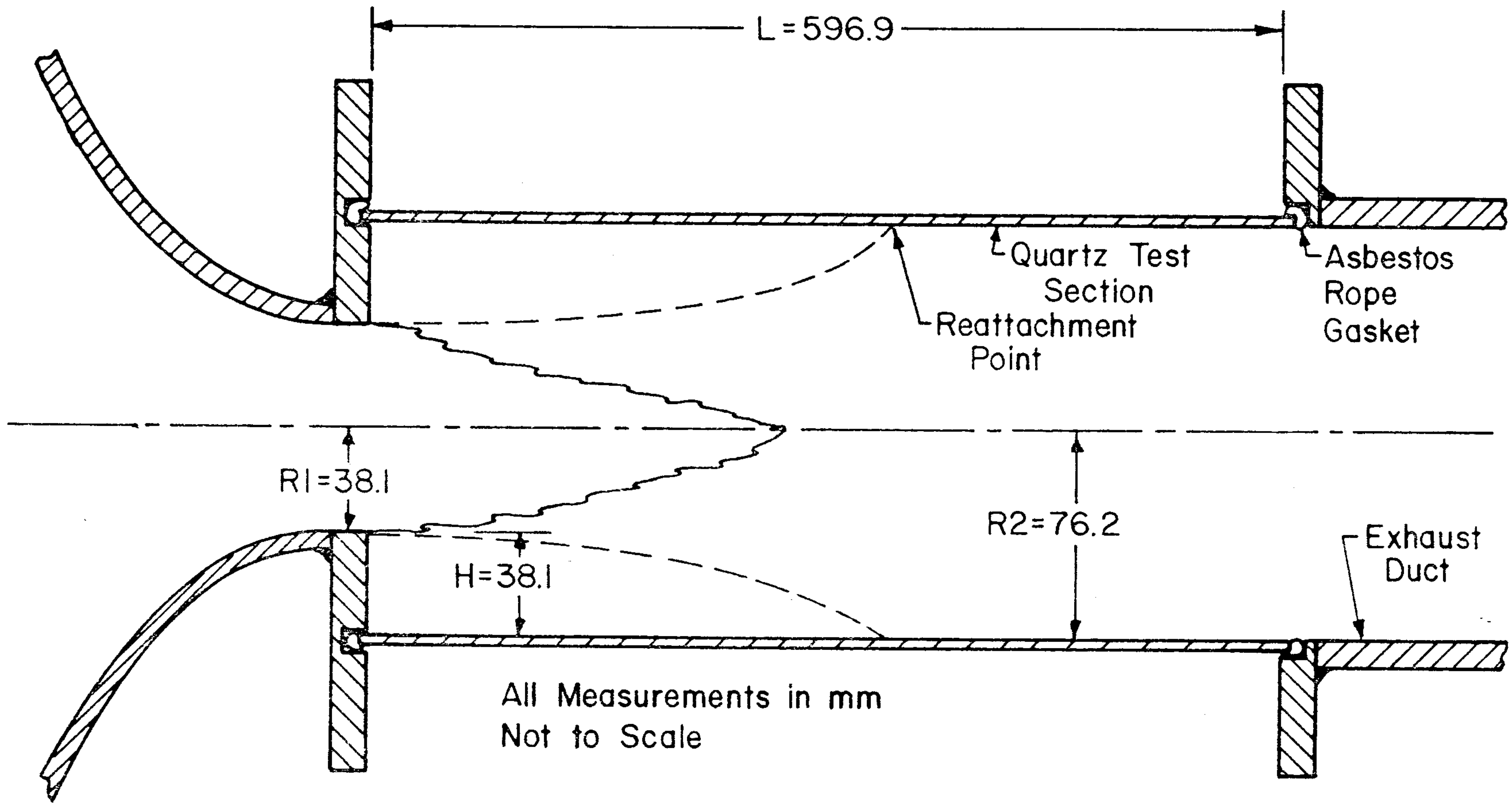

Figure 4. Test section

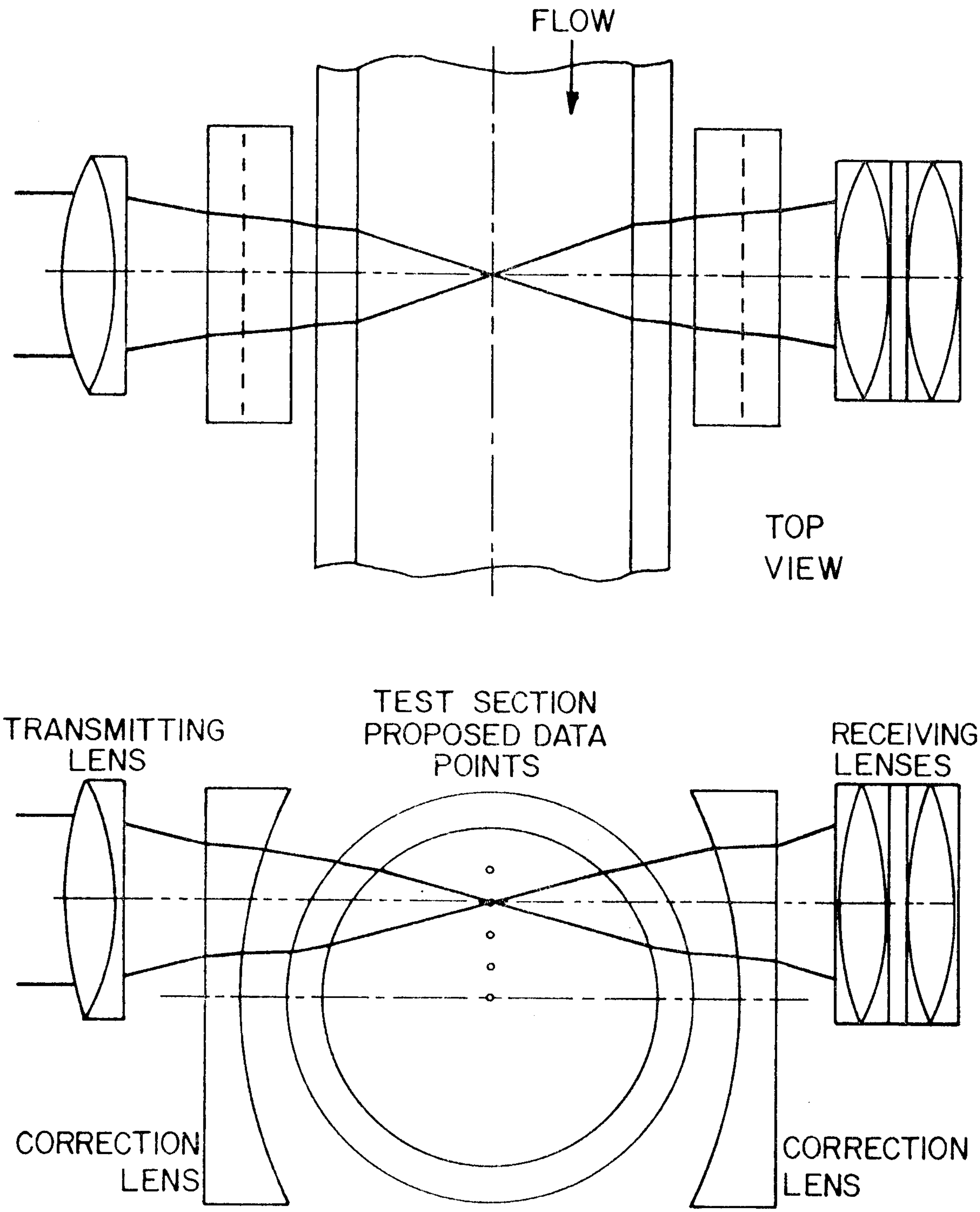

Figure 5. Correction lens system

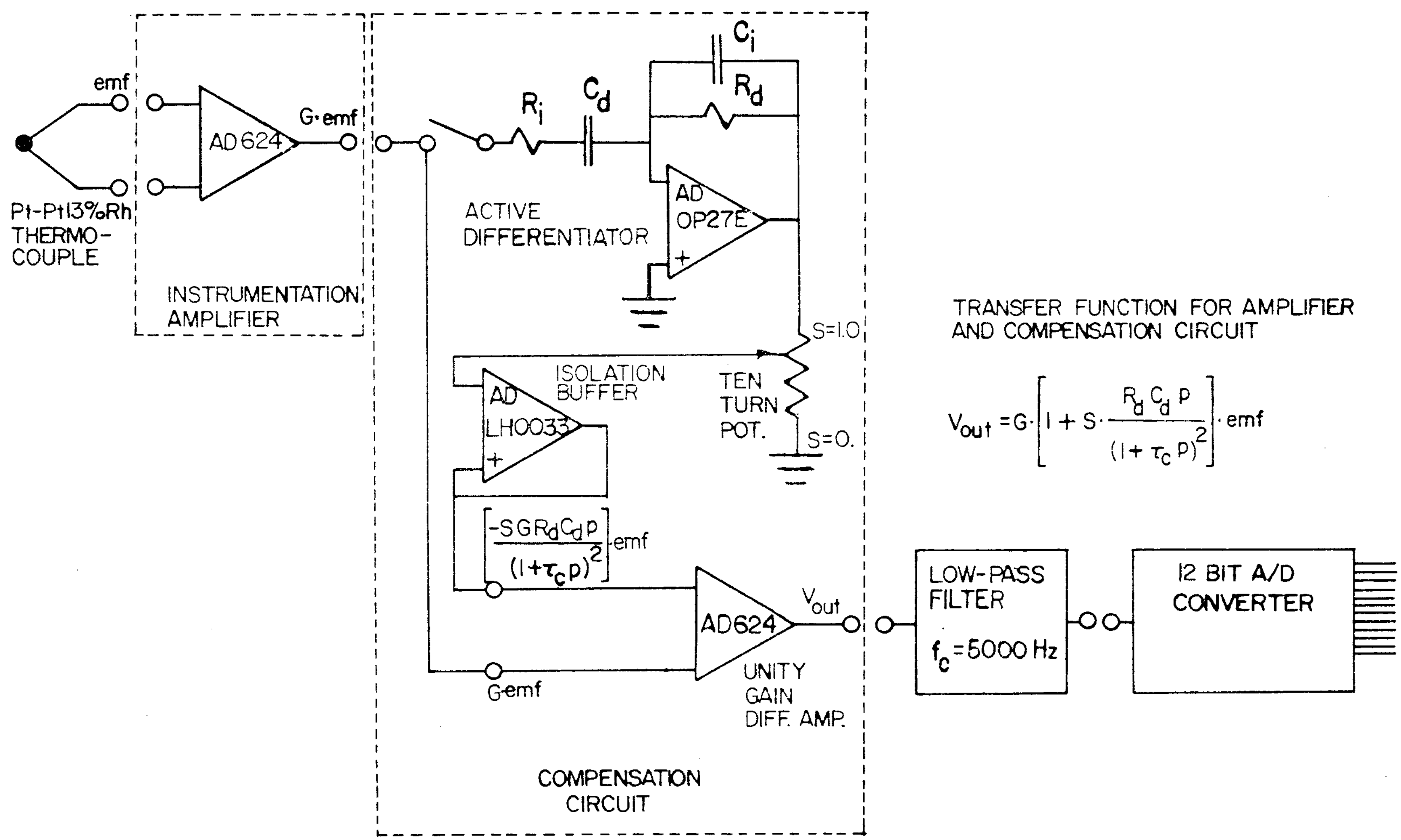

Figure 6. Electronic compensation circuit

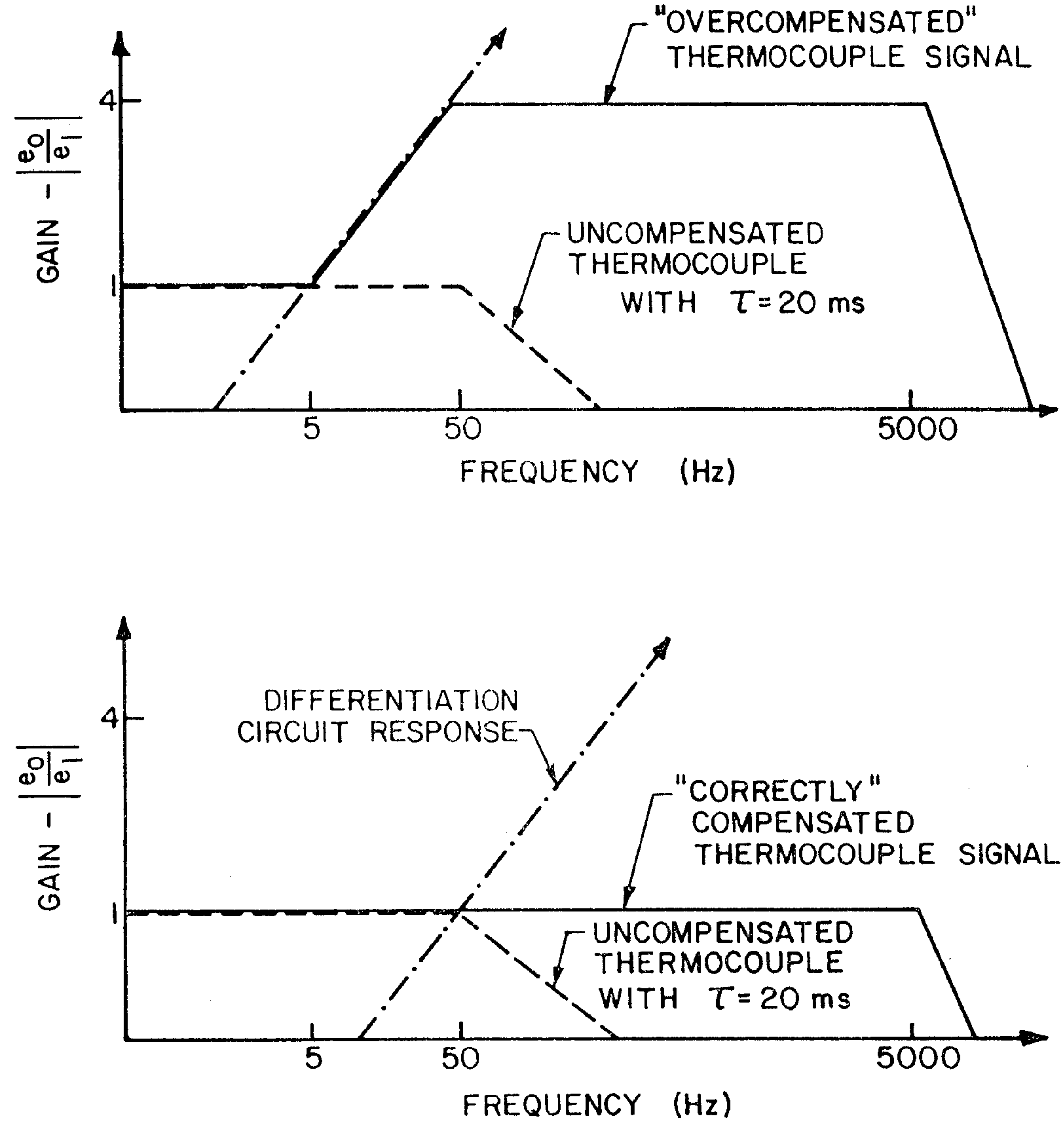

Figure 7. Bode plot of thermocouple response

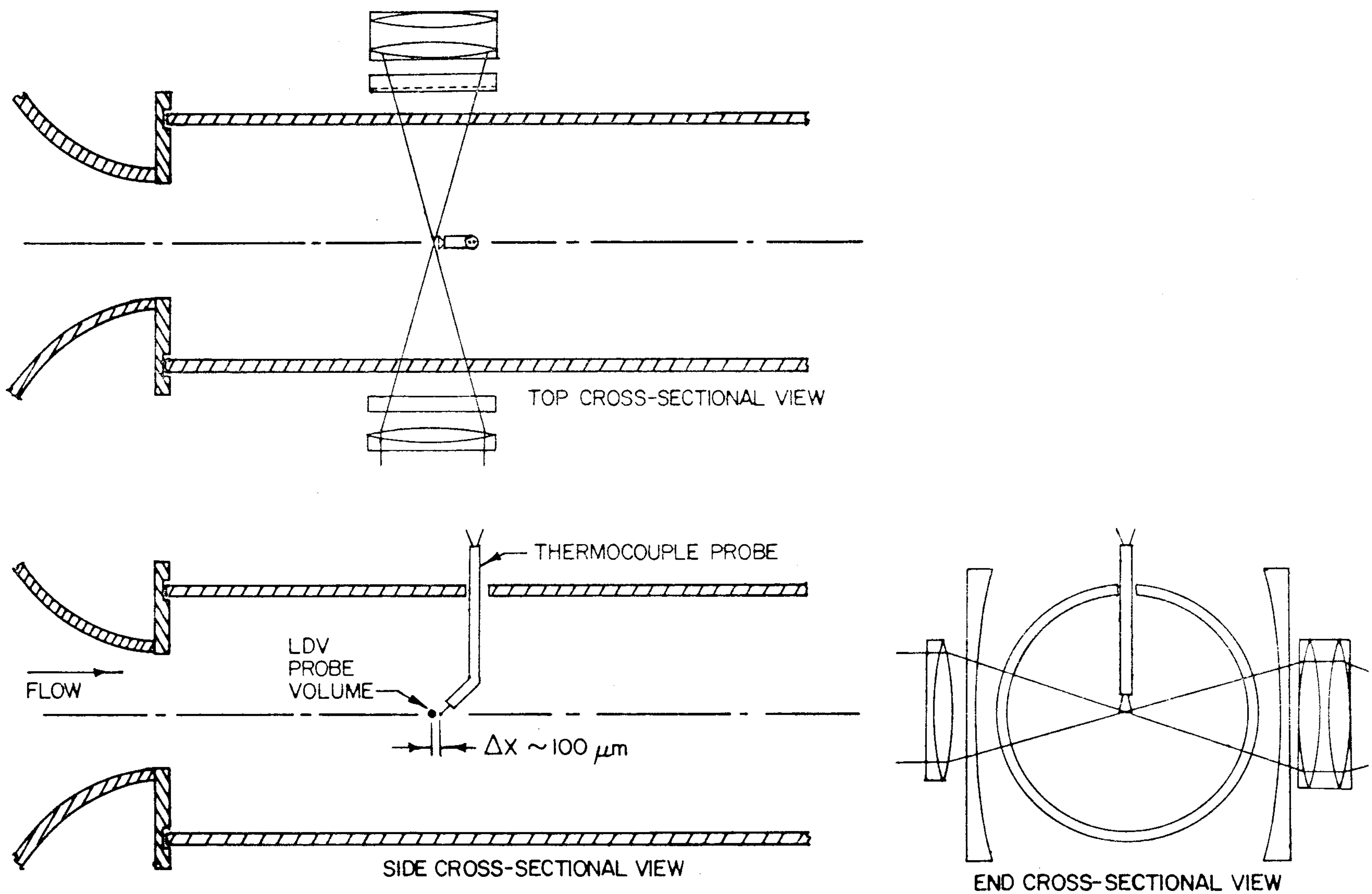

Figure 8. Thermocouple probe orientation

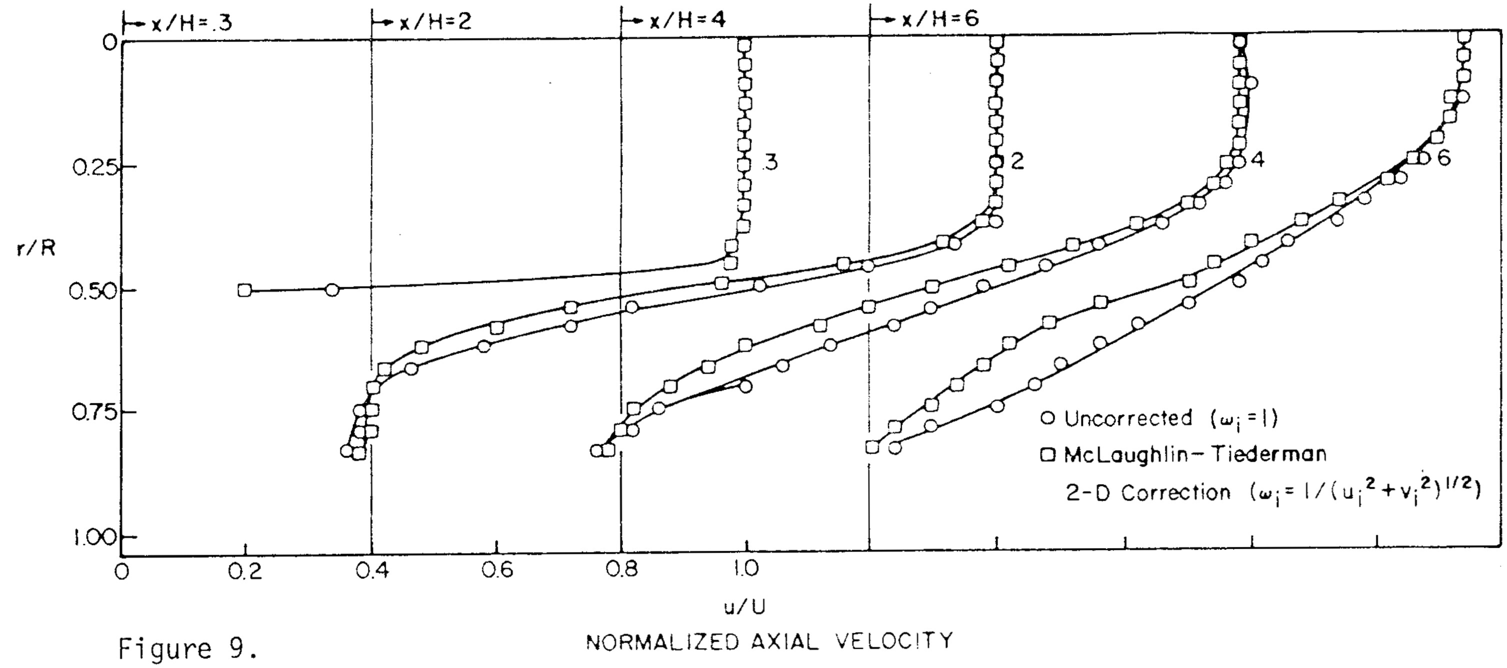

Figure 9.

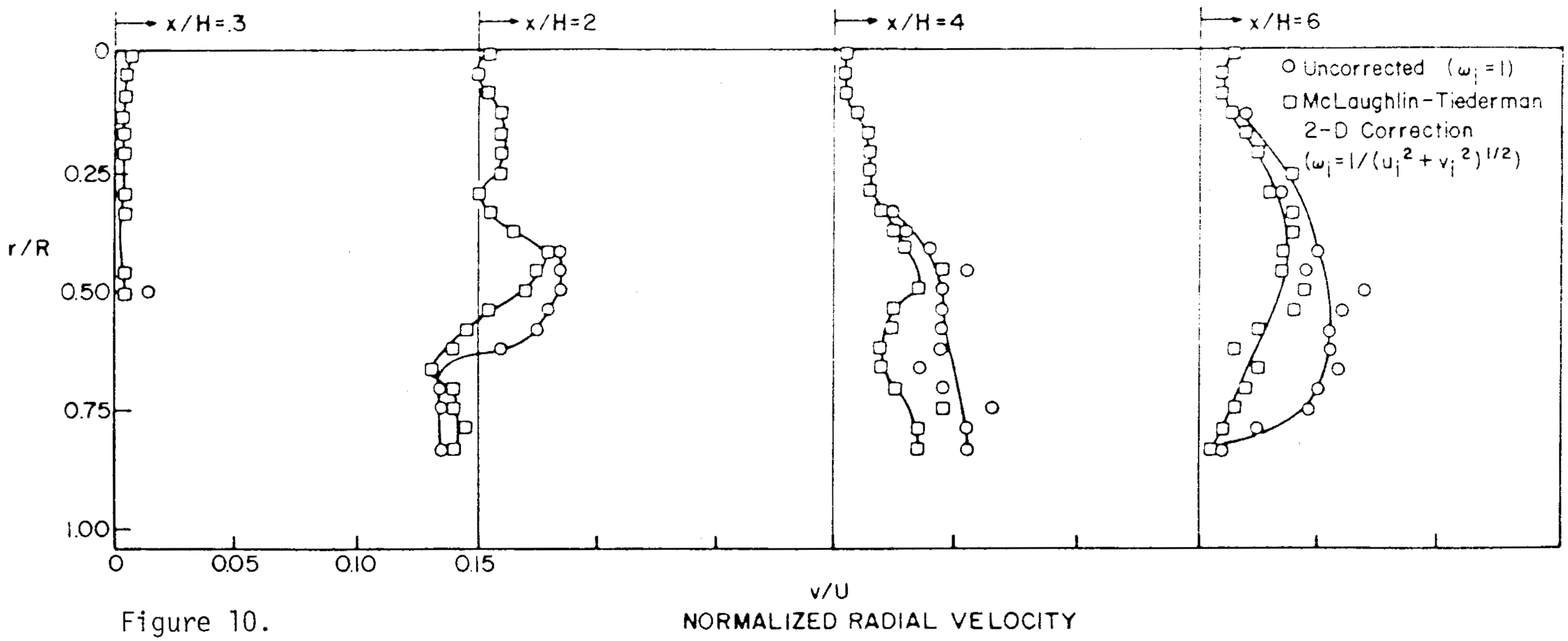

Figure 10.

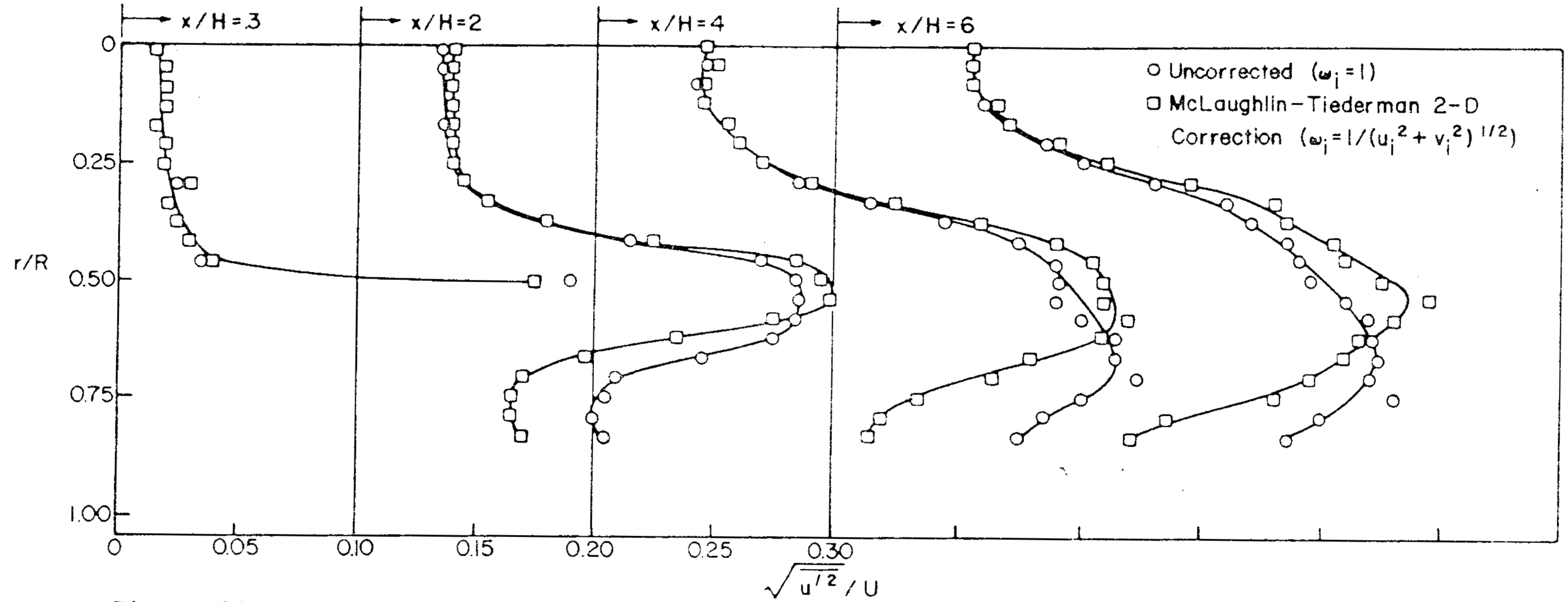

Figure 11.

NORMALIZED AXIAL TURBULENCE INTENSITY

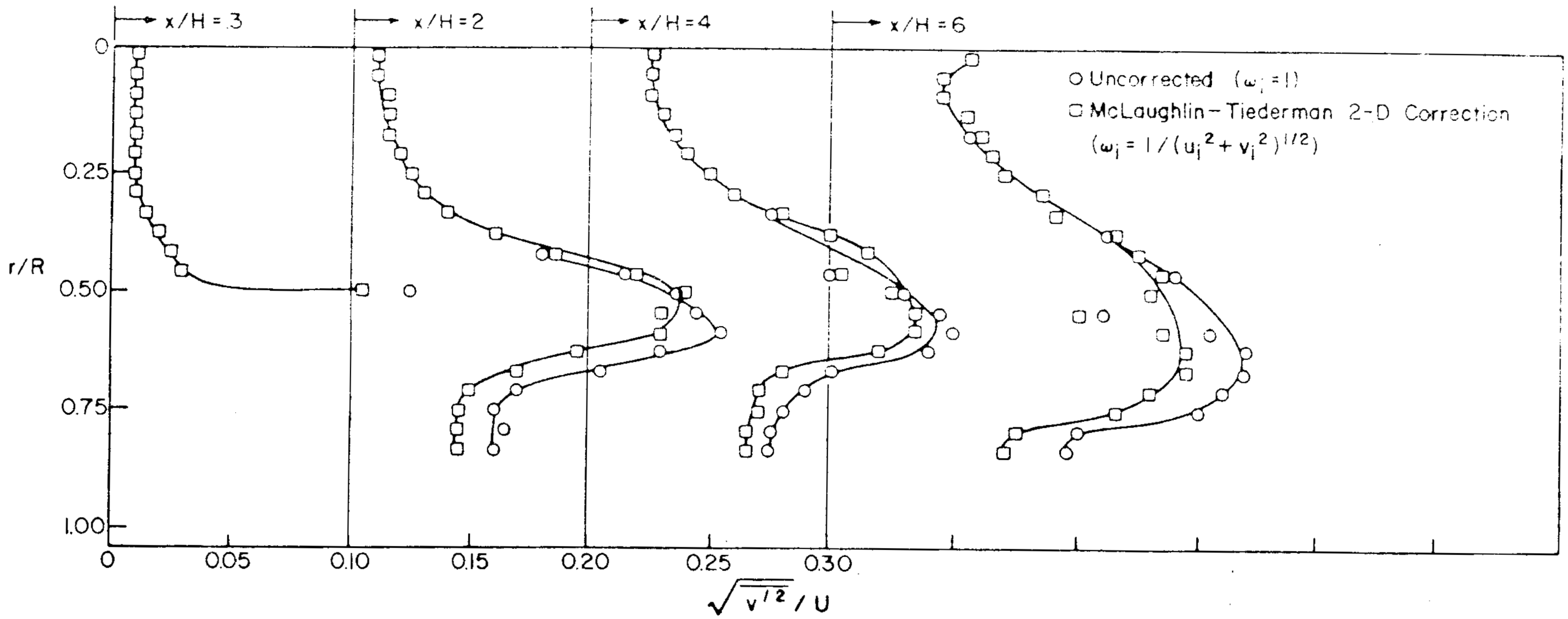

Figure 12.

NORMALIZED RADIAL TURBULENCE INTENSITY

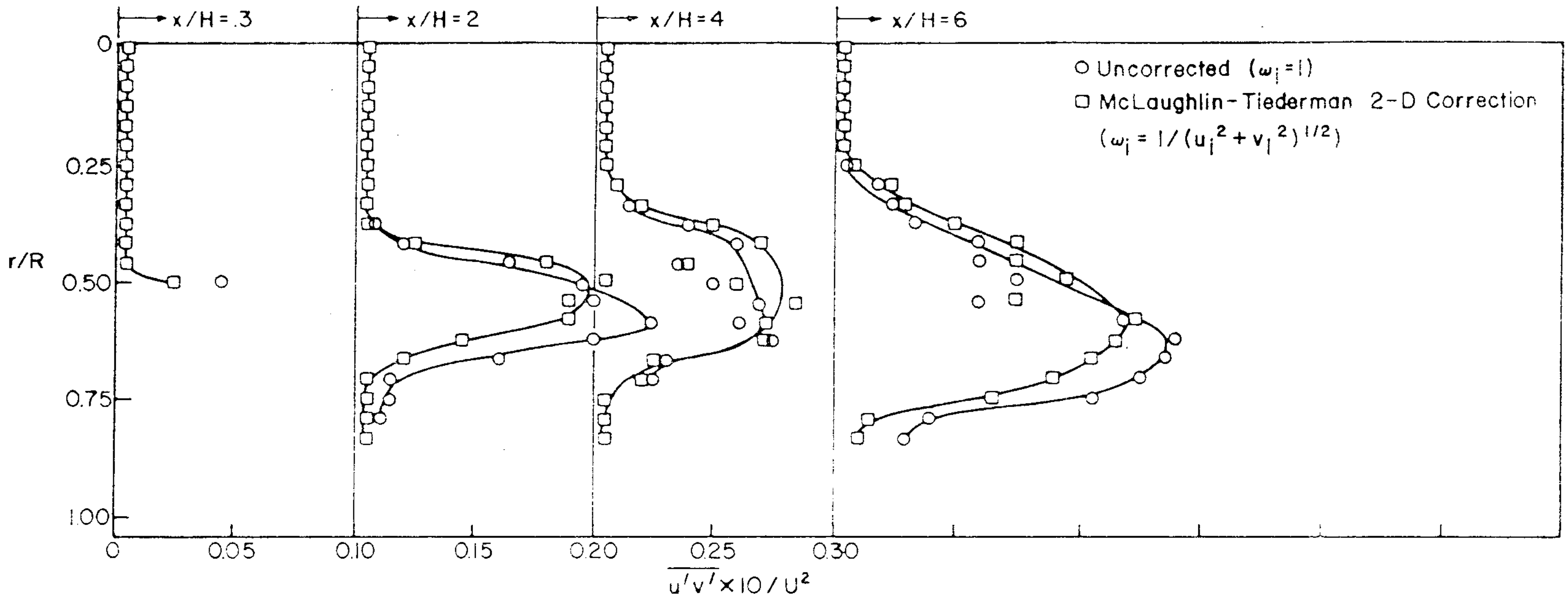

Figure 13

NORMALIZED REYNOLDS STRESS